Wavefront Sensing and Control for the Next Generation Space Telescope

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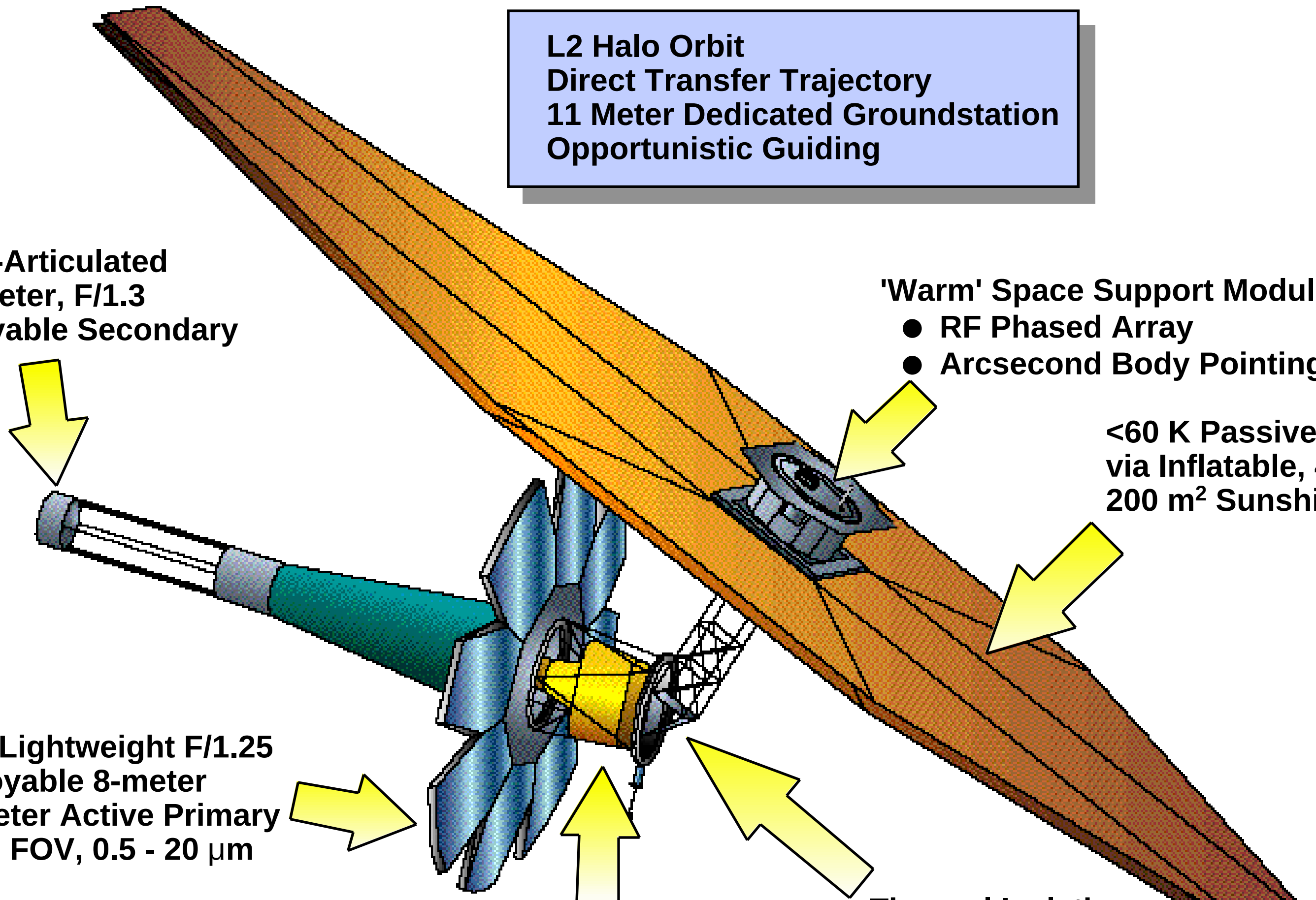
Next Generation Space Telescope

NGST "Yardstick" Point Design

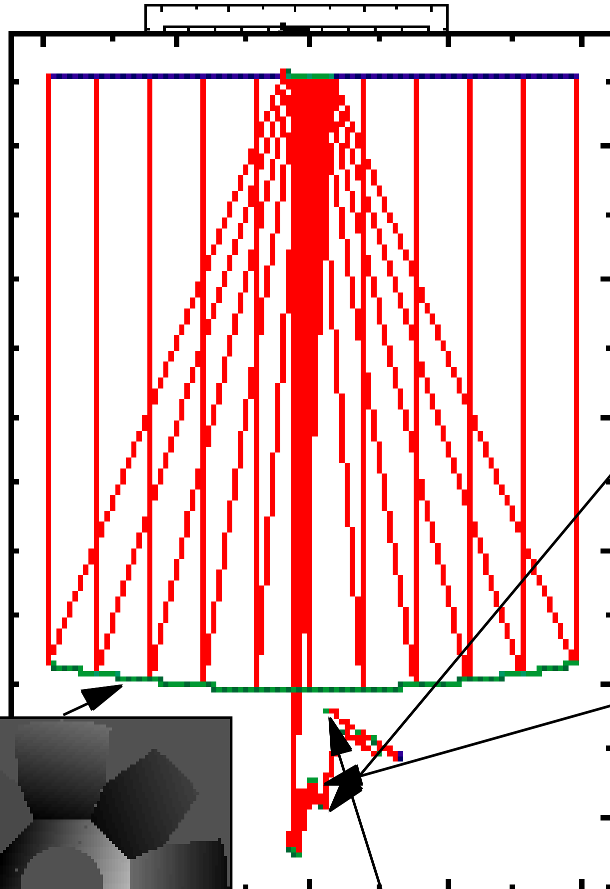


A1130.007 OD7

NGST Yardstick Optics

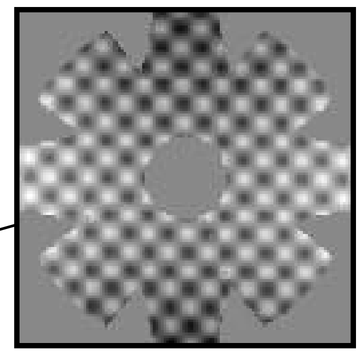
NGST Yardstick

All-Beryllium configuration
8-Petal PM
8 meter aperture
F/1.25 primary
F/24 system



Guiding

Spacecraft ACS accurate to 1 asec
FSM loop closed at 6 Hz
FSM provides < 5 masec jitter stability

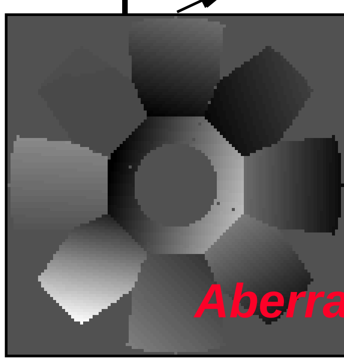


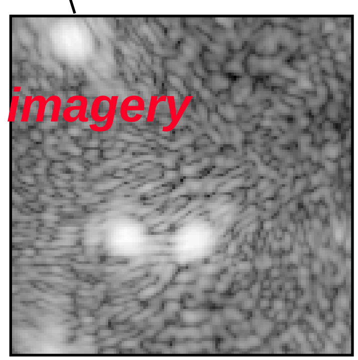
Deformable Mirror

349 actuators
4 mm pitch
±2 um stroke
Cryogenic operation

Segmented PM

3 -6 DOF control per segment





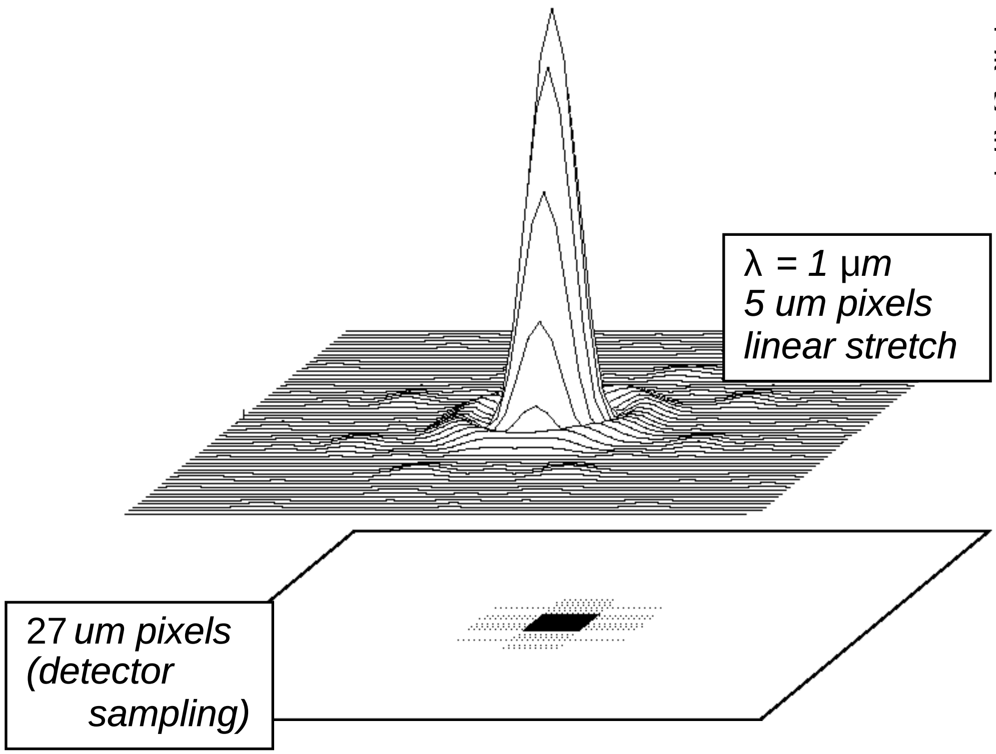
Near IR Camera

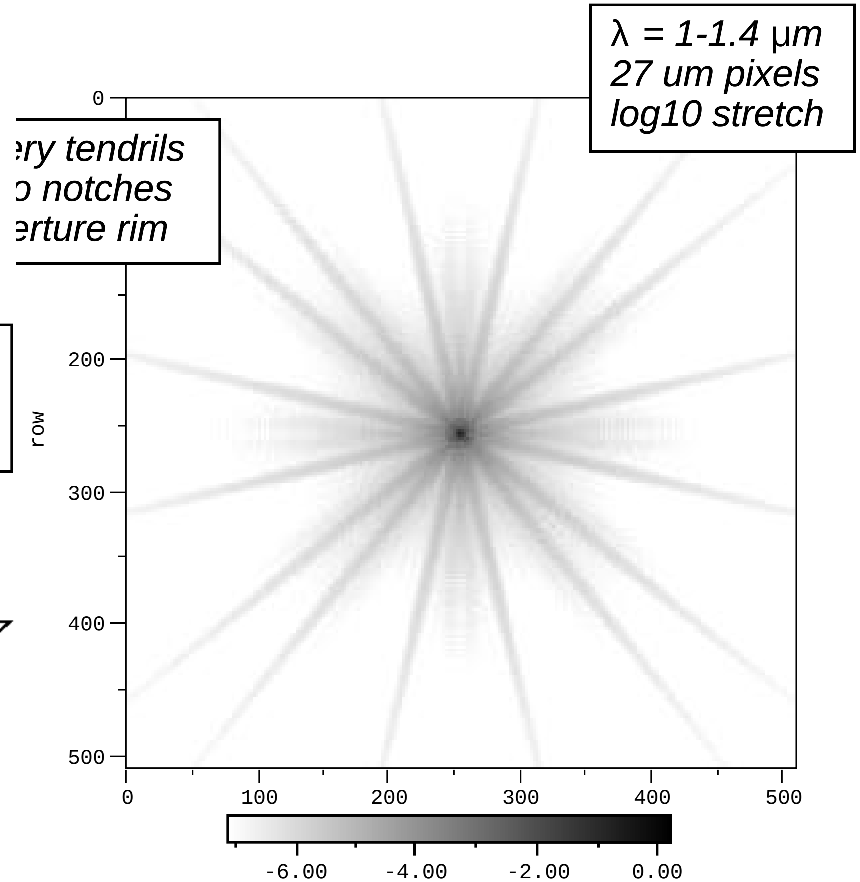
Used for WF sensing
27 um / 39 masec pixels
2 - 5 um wavelength
4 channels

Far IR Camera

6 - 16 um wavelength

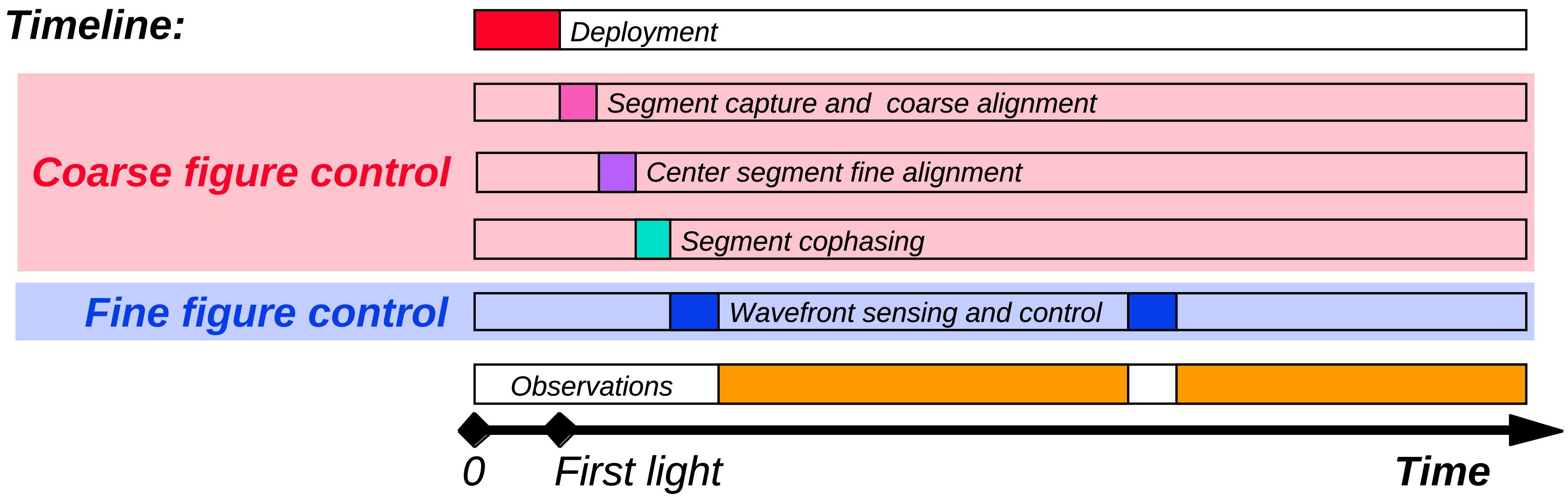
Nominal Point Spread Function





- **Central pixel contains:**
  - **50% of total energy at l = 1 mm** **5% at λ = 4 µm**
  - **18% at λ = 2 µm** **2% at λ = 6 µm**
- **All cameras diffraction limited across full field**
  - **SR = 75% (relative to annular aperture) in Near IR camera**
  - **WFE = 21 nm on-axis**

NGST Baseline WF Control



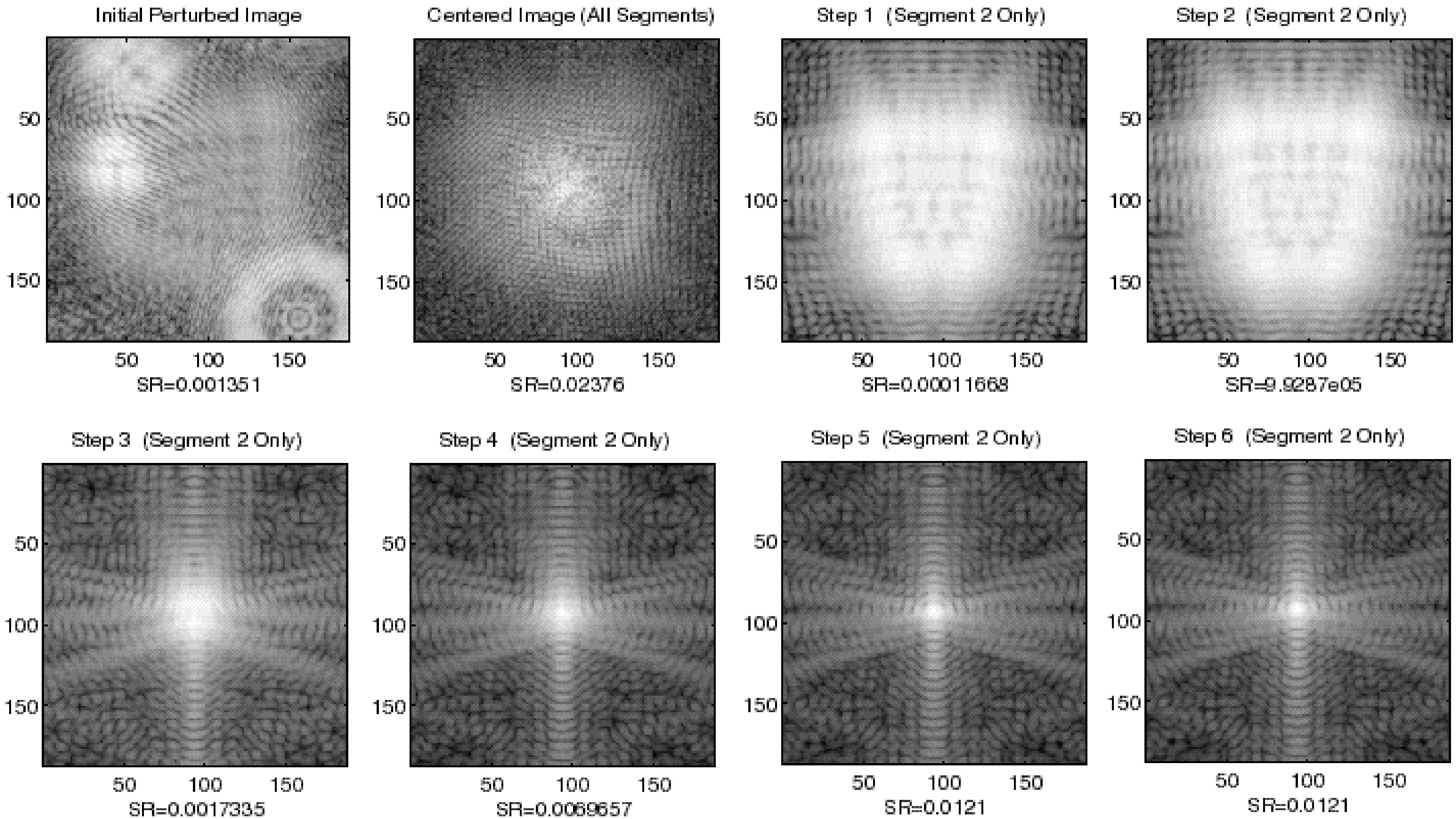
Initial Capture, Alignment and Phasing

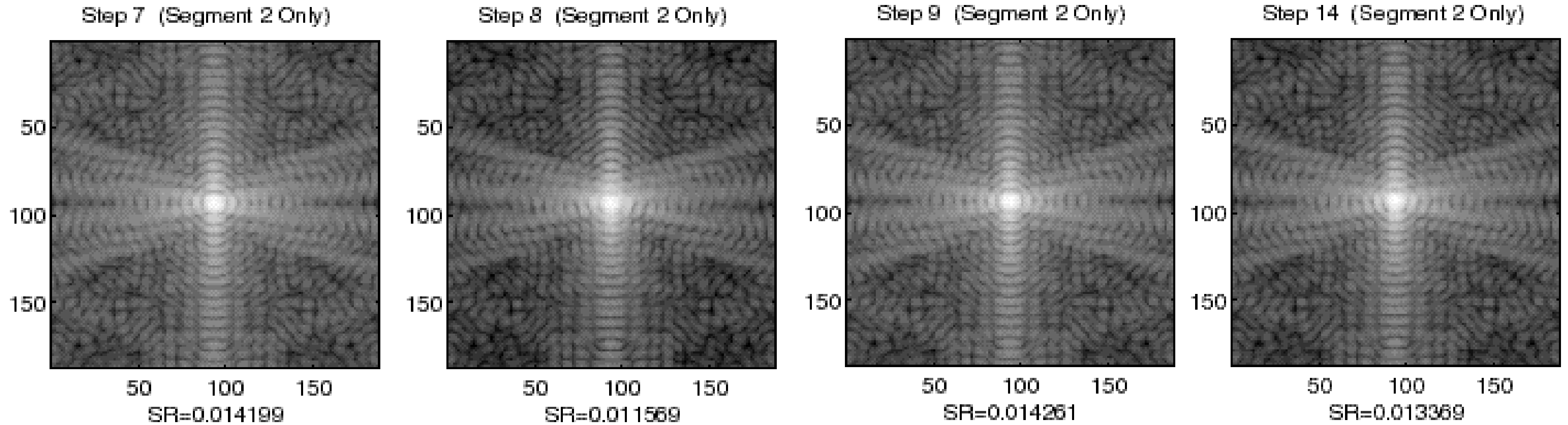
- **Initial alignments may be quite poor** *(wfe < 1 cm)*
- **Segment capture and coarse alignment: Scan tip/tilt to find segment spots (images of a calibration star) and drive spots to target locations. Scan focus and place segments at best focus** *(wfe < 20 um)*
- **Center segment fine alignment: Best alignment of center segment singly with SM and instruments.**
- **Segment cophasing: Coalign/cophase each segment in turn to center segment** *(wfe < 2 um)*
- **Wavefront sensing and control: tweak final segment phasing, set deformable mirror** *(wfe < 150 nm)*

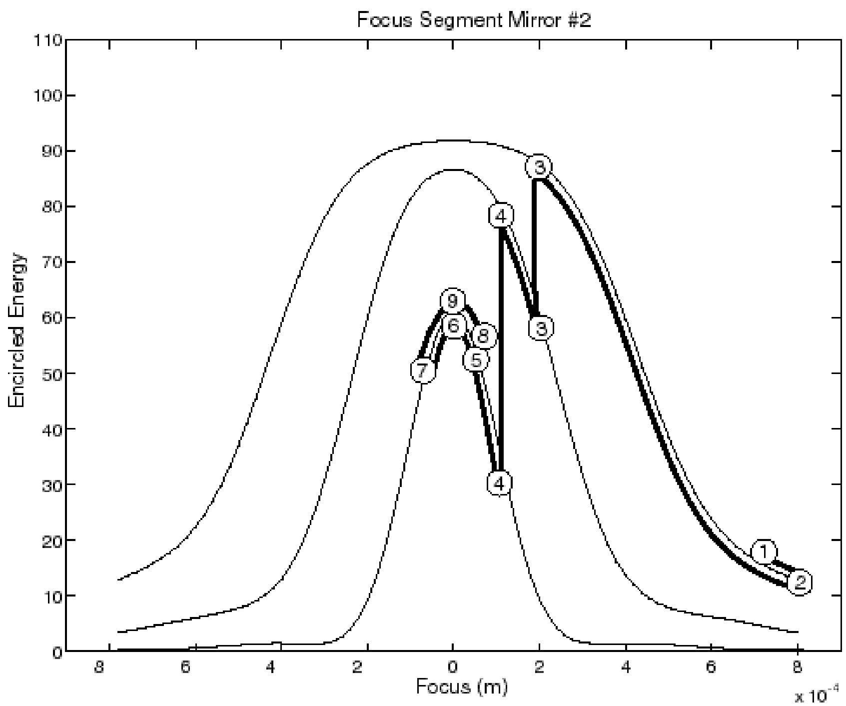
Initial Capture and Alignment

- Expect large, random initial misalignments
- Capture and align a single segment spot:
  - Segment is tilted slightly, frames differenced, and difference frame is thresholded
  - If difference frame exceeds threshold, spot is centroided, and the spot is driven to the center of the field
  - Otherwise, scan segment to next (4 amin) FOV and repeat
- Focus each single segment spot:
  - Segment is scanned in focus and encircled energy is recorded
  - Realigned as necessary to keep spot centered
  - Segment placed at best focus
  - Repeat for each segment

Capture and Alignment Example

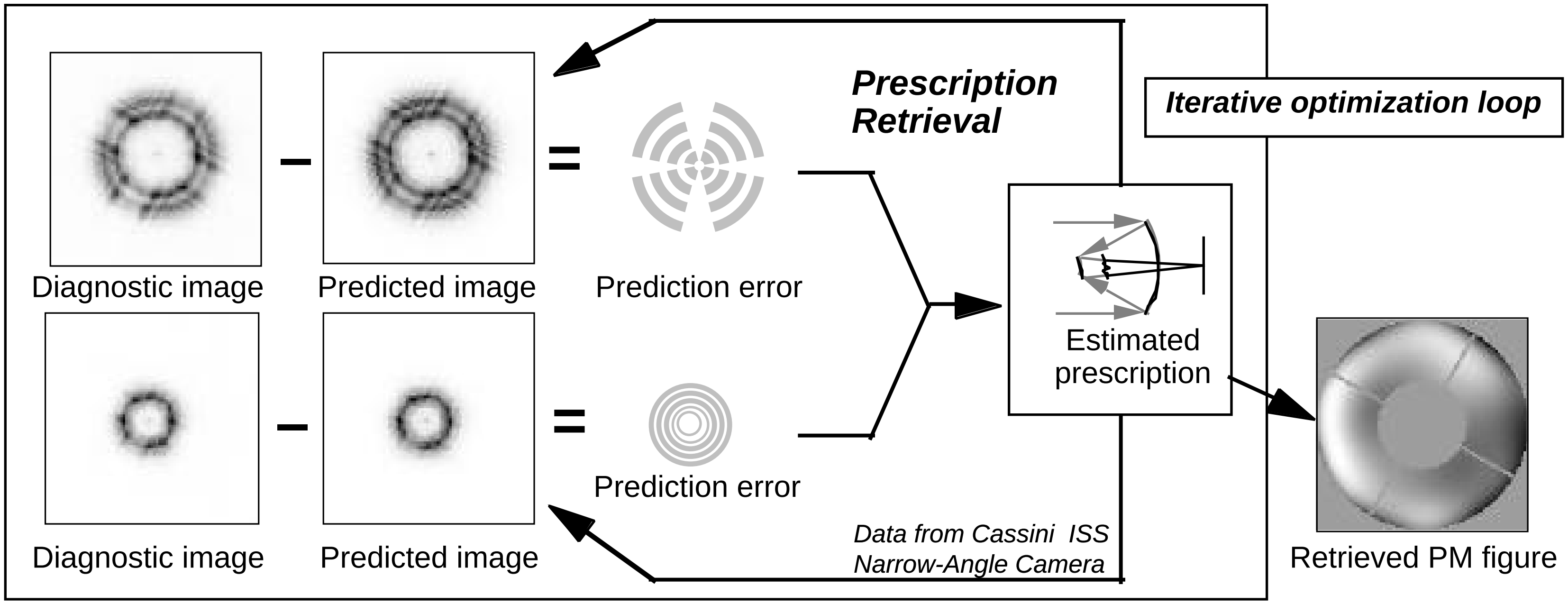






- **Encircled energy metrics used in single-segment focus scan**
- **Metric circle radii decrease as focus improves, from 100 pixels, to 30 pixels, to 3 pixels.**

Alignment of Center Segment, SM, ISIM

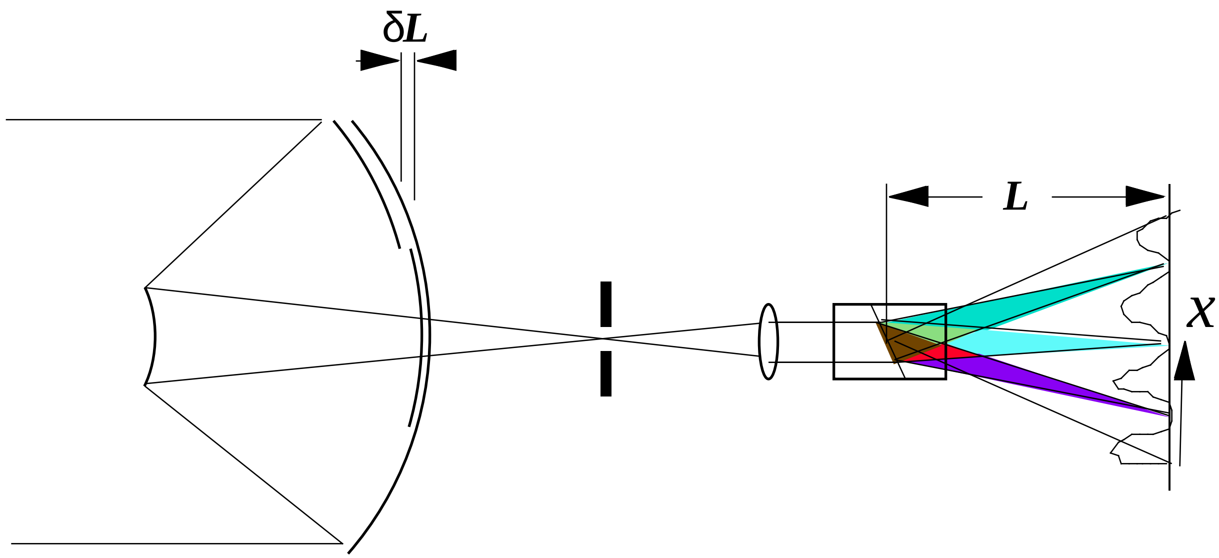


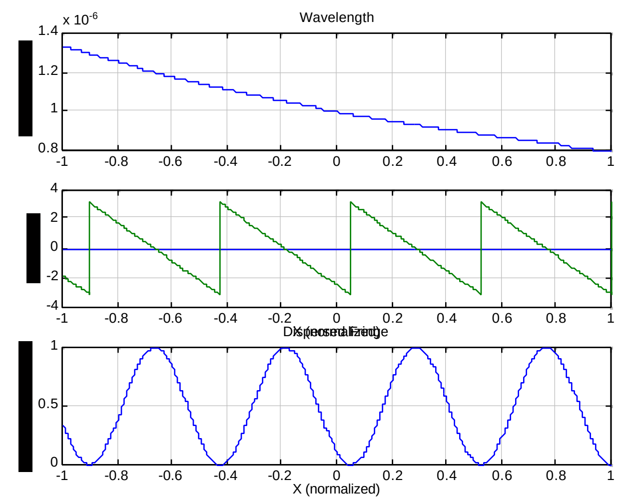
- Scan segment in focus, center at peak
- Take deliberately defocussed images (both sides of focus)
- Process using prescription retrieval software to determine best alignment
- Move segment to best alignment
- Begin FSM guiding

Cophase Segments Using DFS

- Begin by coaligning 2 segment spots
- Then rotate grism into beam to form Dispersed Fringe Sensor (DFS)
- DFS provides immediate readout of relative phase
- Move segment and repeat to ID sign
- Drive segment to null phase difference
- Repeat with other segments

Dispersed-Fringe Sensor for Coarse Phasing





- Phase difference **δ*L*** is modulated by wavelength (which varies with ***x***), causing dispersed spots to interfere
- Field at any ***x*** on detector sums contribution from 2 dephased segments:

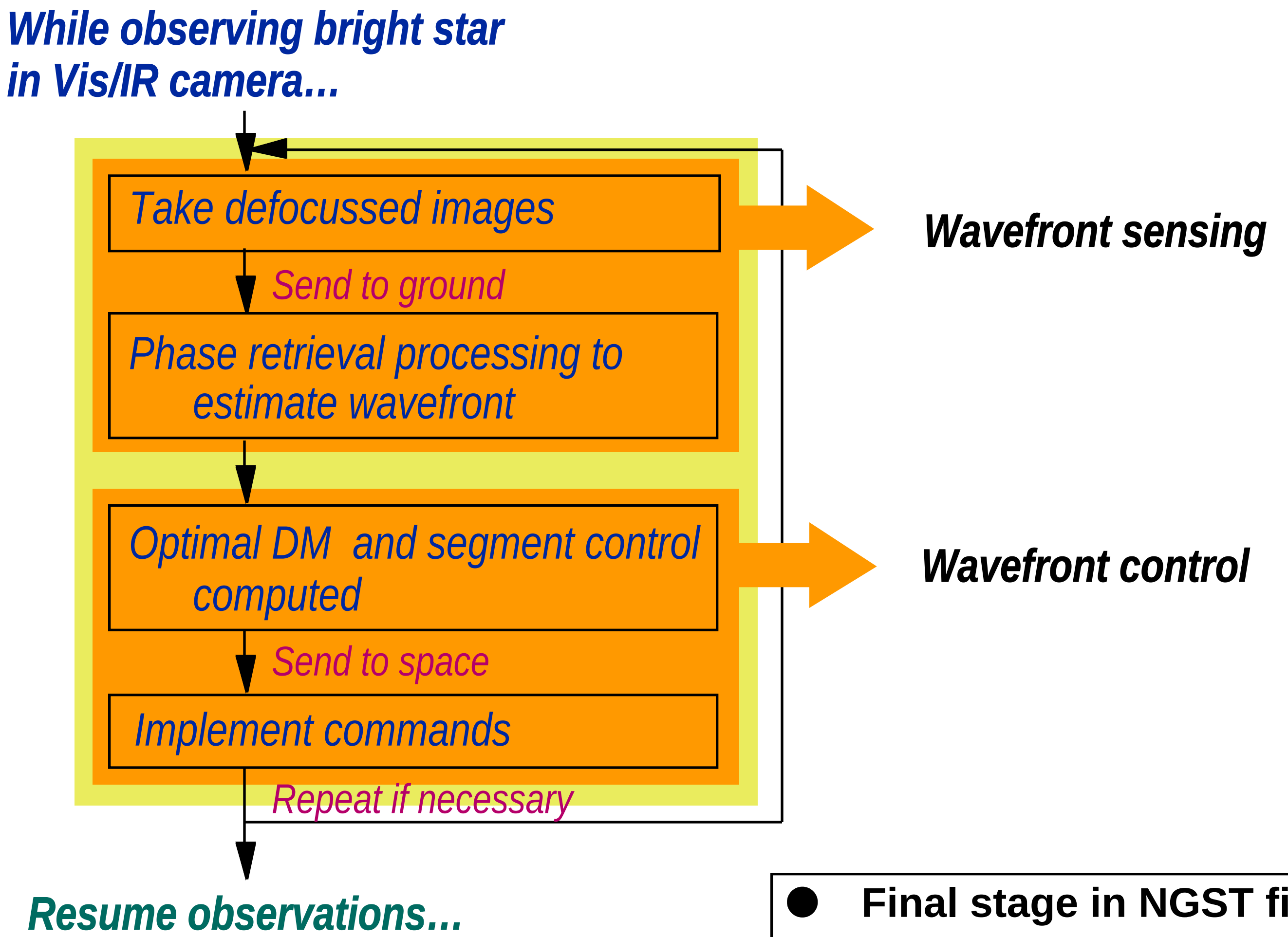
$$E = E_0 \exp(i\,(2\pi/\lambda(\boldsymbol{x}))\,\boldsymbol{L})\ \ (1 + \exp(i(2\pi/\lambda(\boldsymbol{x})\ \delta\boldsymbol{L})$$

- Fringe spacing along ***x*** is inversely proportional to **δ*L***
- Sign is ambiguous
- DFS in operation at Palomar Testbed Interferometer

Cophase Segments Using WLI

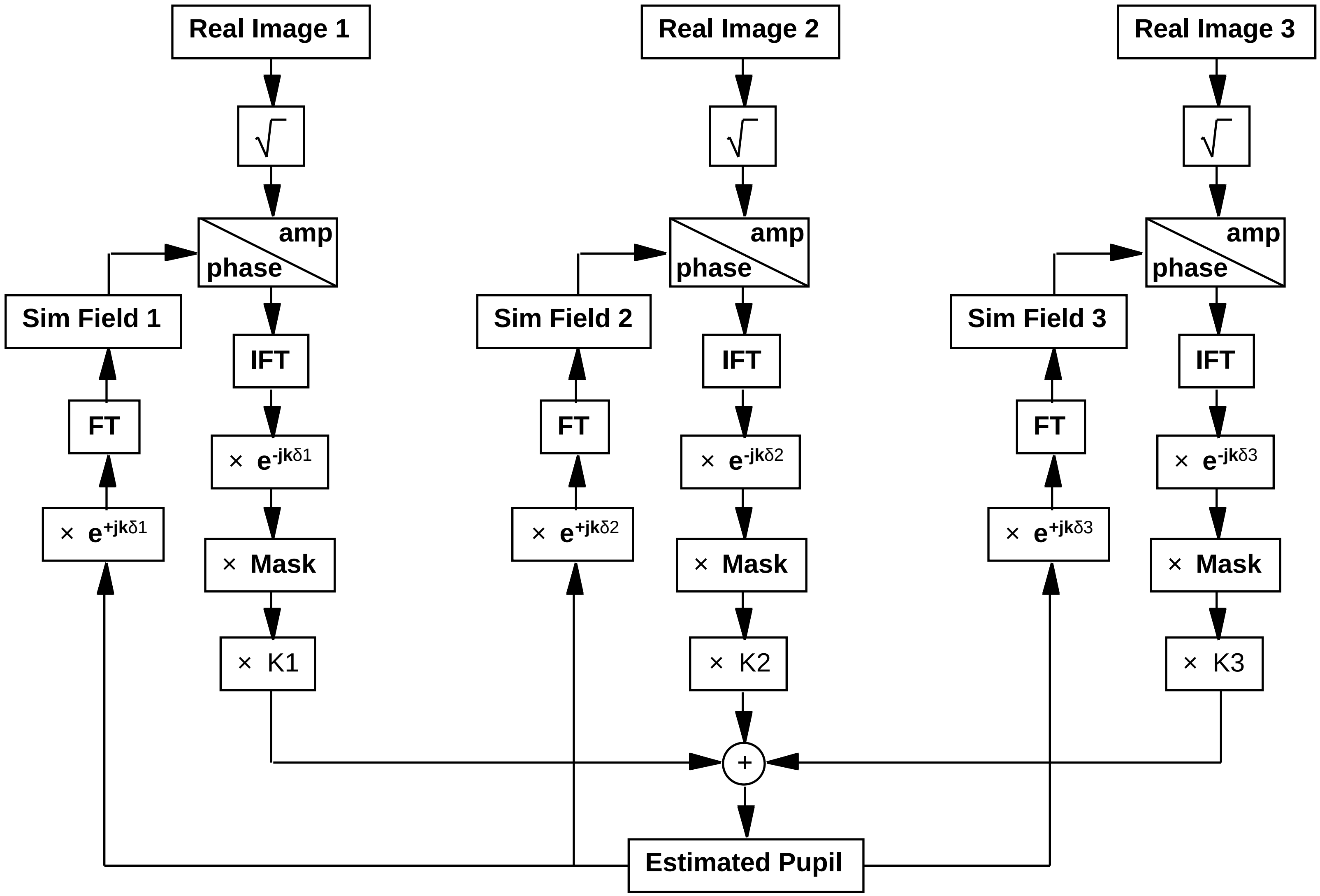
- Begin by coaligning 2 segment spots
- Use finite-bandpass filter
- Scan segment in defocus DOF, recording peak pixel DN values
- Peak DN oscillates with $\lambda/2$ period within envelope defined by bandpass of filter
  - DN history processed to ID best phasing
- Drive segment to best phase position
- Repeat with other segments
- Used by Fourier-Transform Spectrometers

Wavefront Sensing and Control



- **Final stage in NGST figure initialization**
- **Performed periodically, following initial alignment, and then as needed to keep image quality**

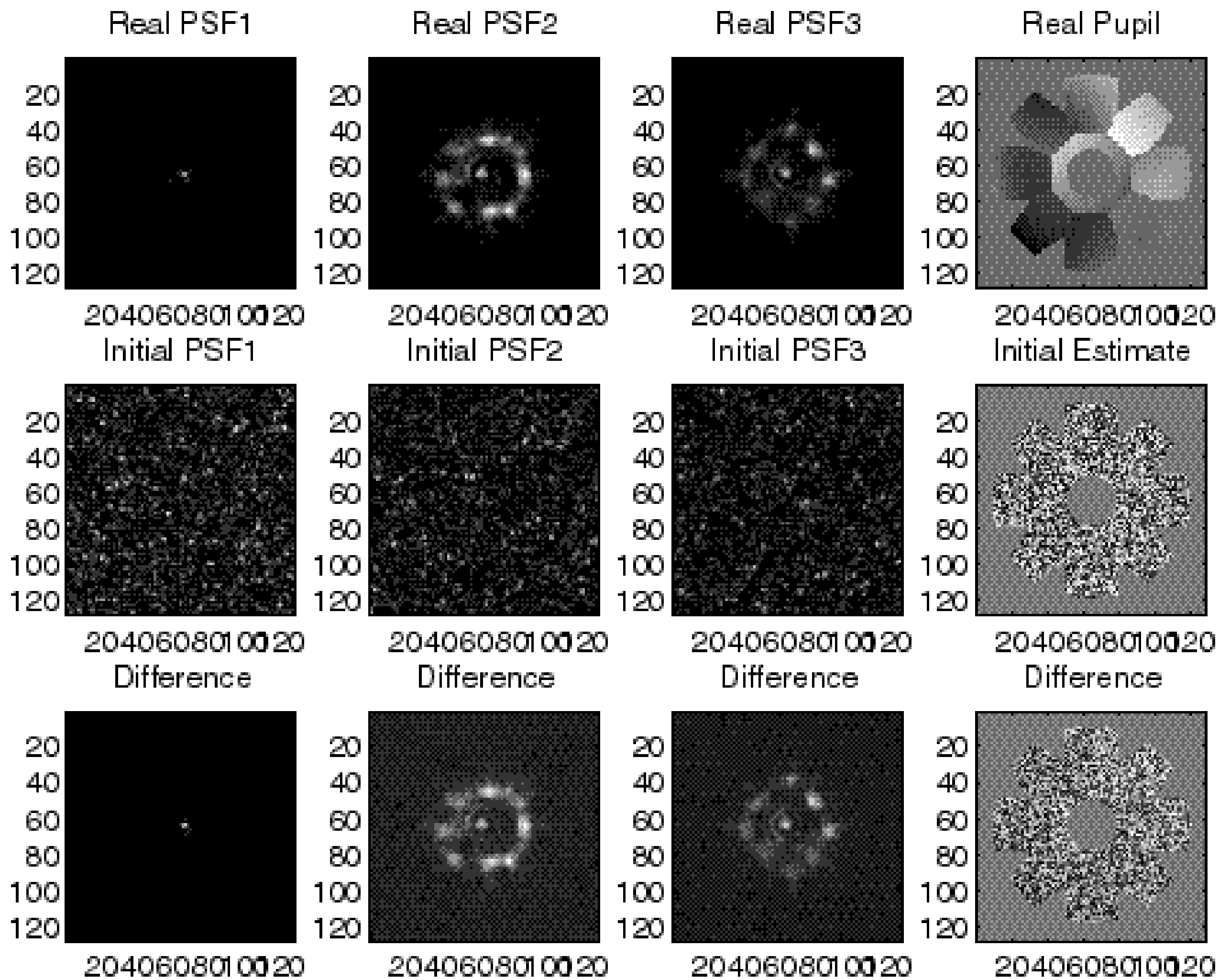
Focus-diverse iterative-transform phase retrieval



WF Sensing Example: Initial Guess

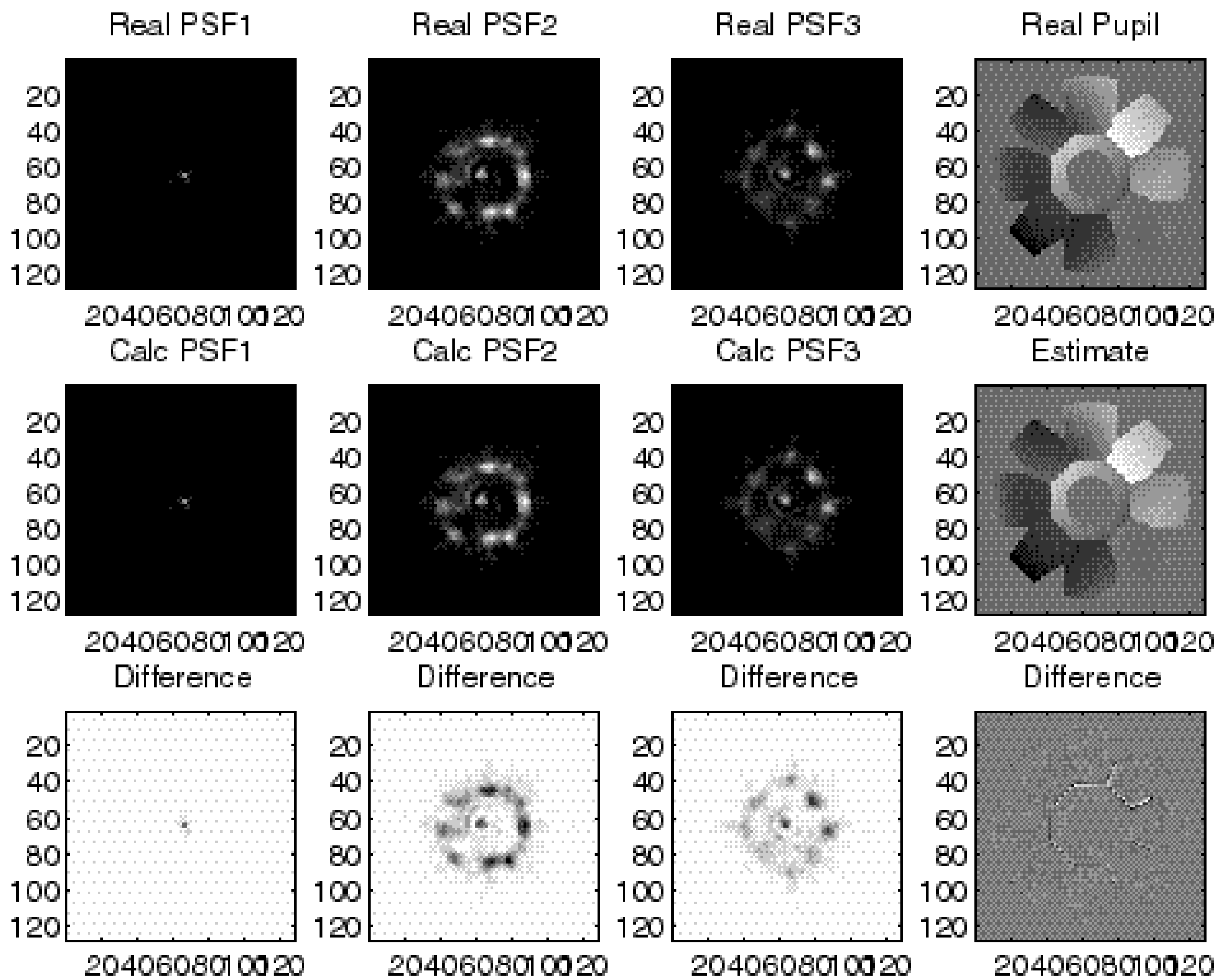
Data:

Model:



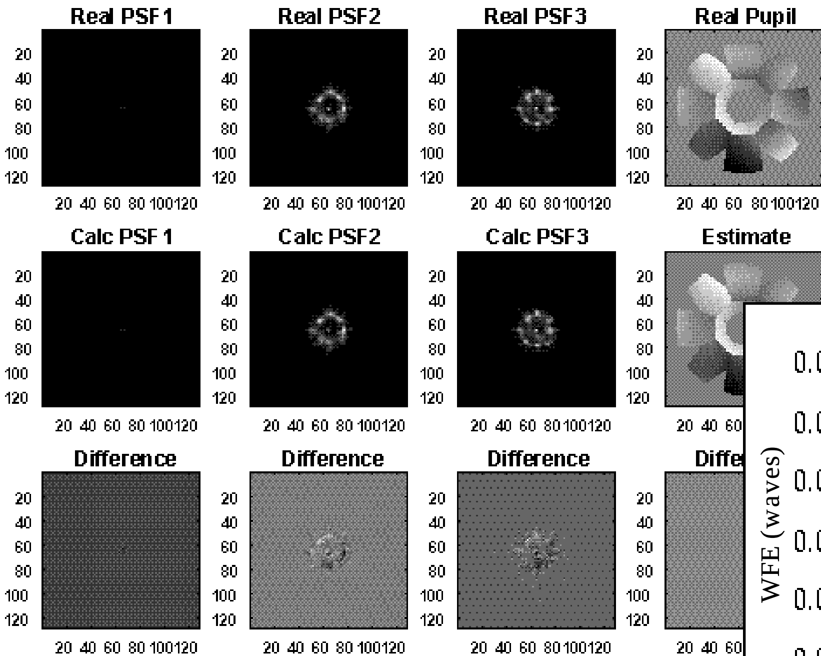
- **Random figure and alignment errors, detection noise**
- **WFE = 1 wave (P-V)**

WF Sensing Example: Final Estimate

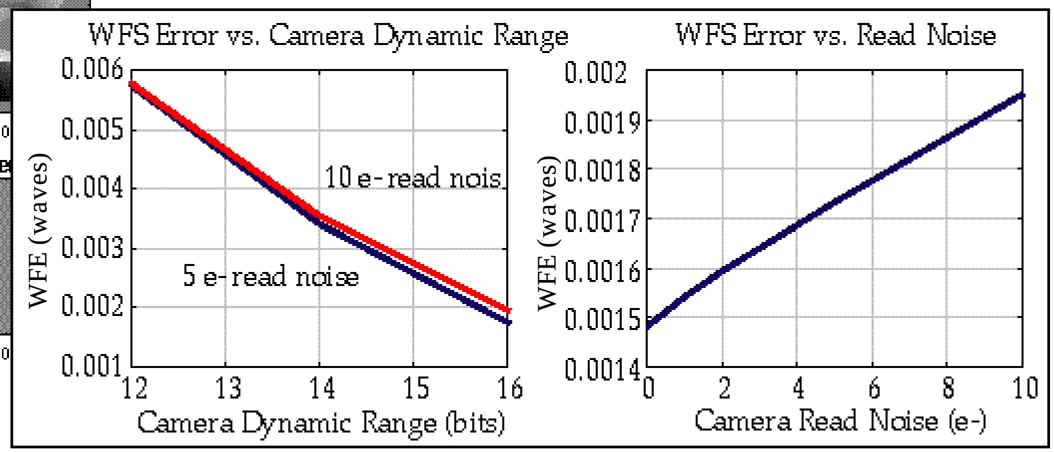


- **Estimate converged to λ/443**

WF Sensing Performance Studies



Nominal WFS performance λ/249 at 2 μm



Performance studies ongoing...

- **Noise sources: shot noise, read noise, stray and scattered light, crosstalk, finite bandpass, jitter, background, resolved object, ...**
- **Algorithms: phase retrieval (several), phase diversity, phase unwrapping, ...**
- **Sensors: Science camera, dispersed-fringe sensor, interferometric WFS, ...**
- **Computing: workstation, supercomputer, on-board supercomputer**
- **Control: actuator errors, DM, PM bending, stroke-vs-density, ...**
- **Validation: DCATT testbed**

Wavefront Control

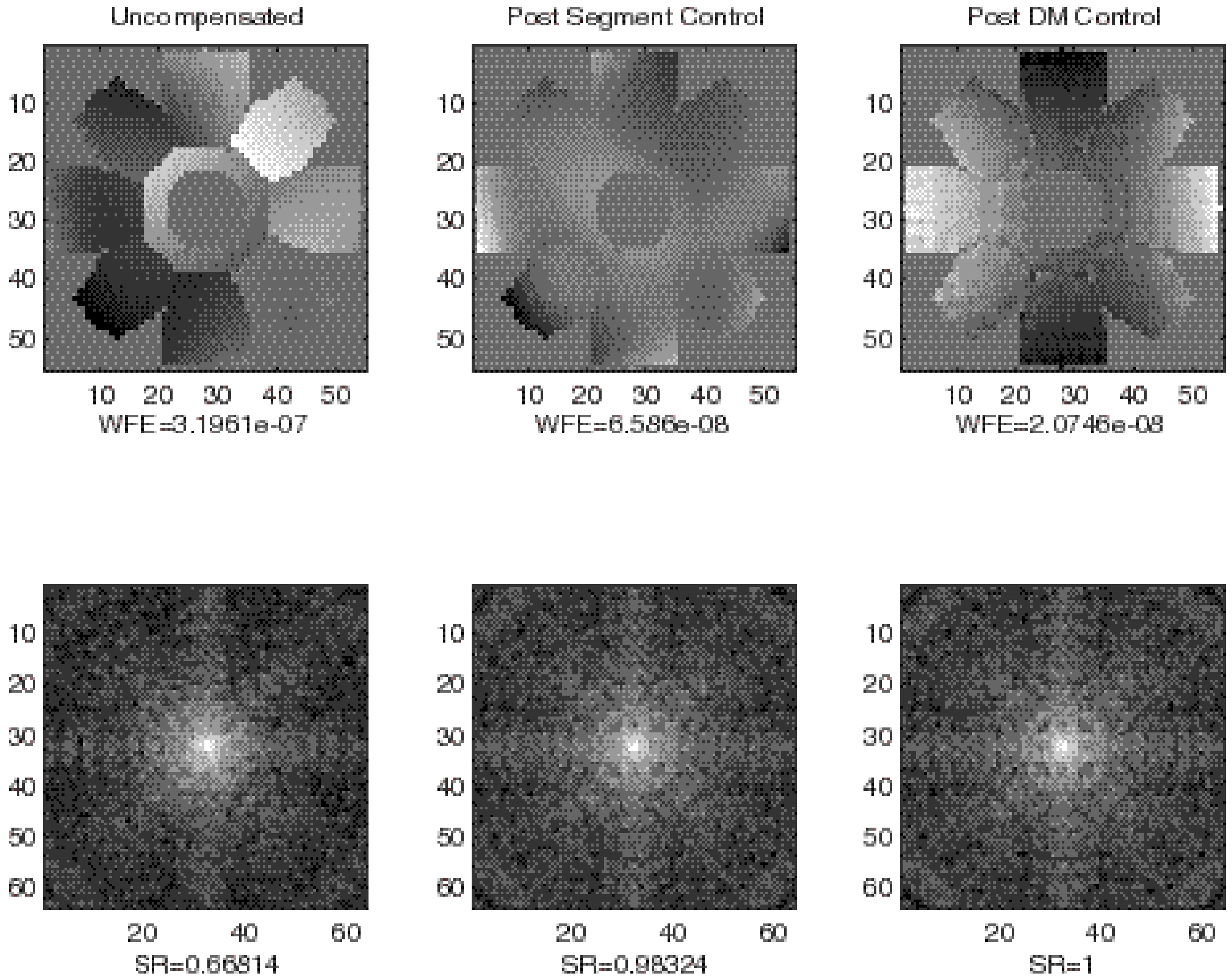
- Control derived using matrix model of optical system
  - $\mathbf{w}$: optical pathlength for each ray
  - $\mathbf{x}$: element states: 6 rigid-body DOF per elt, plus Zernike deformation terms, plus 1044 FEM node displacements
  - $\mathbf{u}$: control: 3 DOF per PM optic and 349 DM actuators
- State transition equation
  - $\mathbf{w} = \mathbf{C}\ \mathbf{x} + \mathbf{CA}\ \mathbf{u}$
- Wavefront sensing generates estimate $\mathbf{w}_{est}$
- Control law minimizes $\mathbf{J} = 0.5\ \mathbf{w}^T\ \mathbf{w}$
  - $\mathbf{u} = -[\mathbf{A}^T\mathbf{C}^T\mathbf{CA}]^{-1}\ \mathbf{A}^T\mathbf{C}^T\mathbf{w}_{est} + \mathbf{du} = -\mathbf{G}\mathbf{w}_{est} + \mathbf{du}$

Evaluating WF Control Performance

- **Post-control residual error**
  - $dw = W - CAG\, w_{est} + CA\, du$
- **Covariance analysis**
  - $W_f = [I - CAGC]\, X\, [I - CAGC]^T + CA\, U\, A^T C^T$
  - $std(WFE) = sqrt(trace(W_f))$

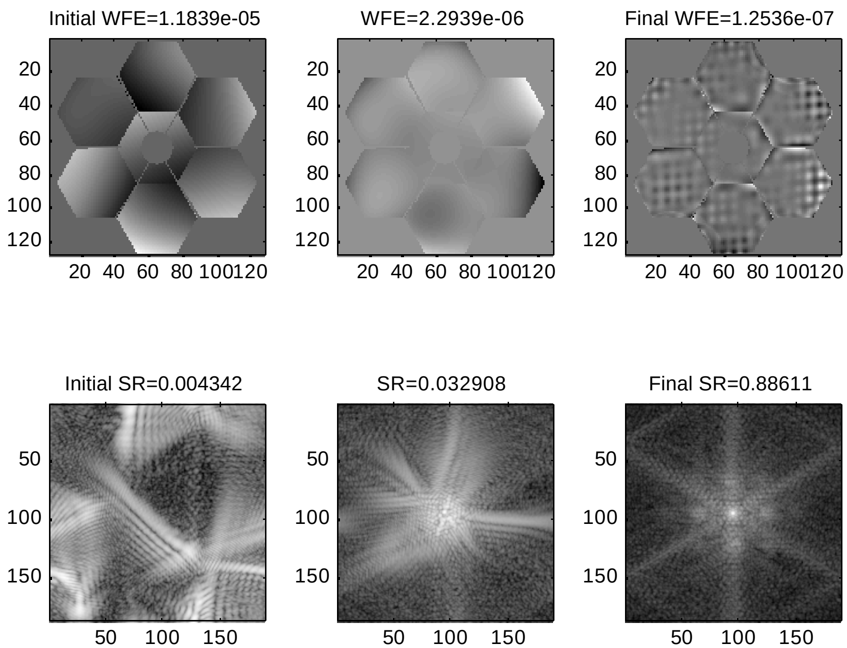
- **Control moves segments to reduce WFE, minimize segment discontinuities**
- **This makes continuous facesheet DM more effective**
- **DM removes remainder of WFE, to spatial resolution**

WF Control of WFS Example

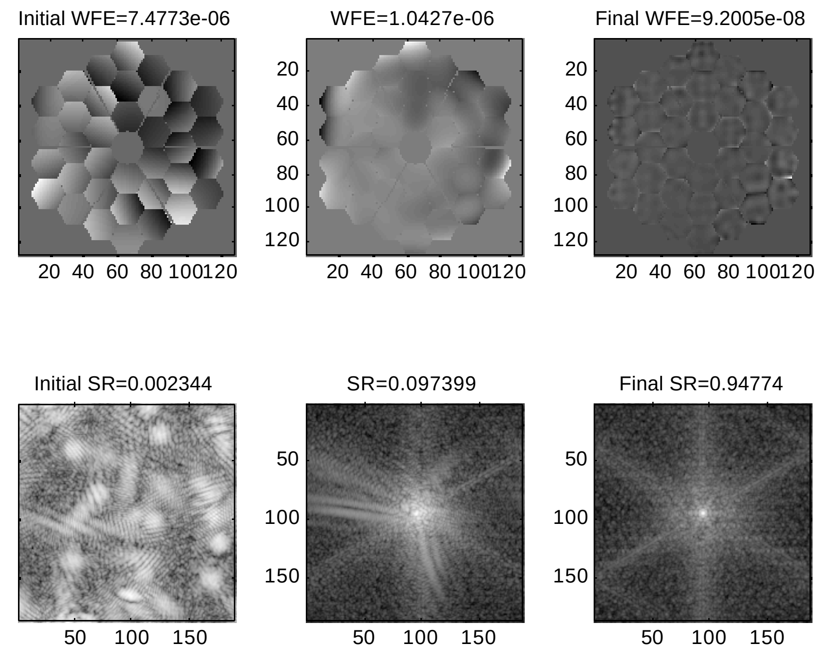


More Examples

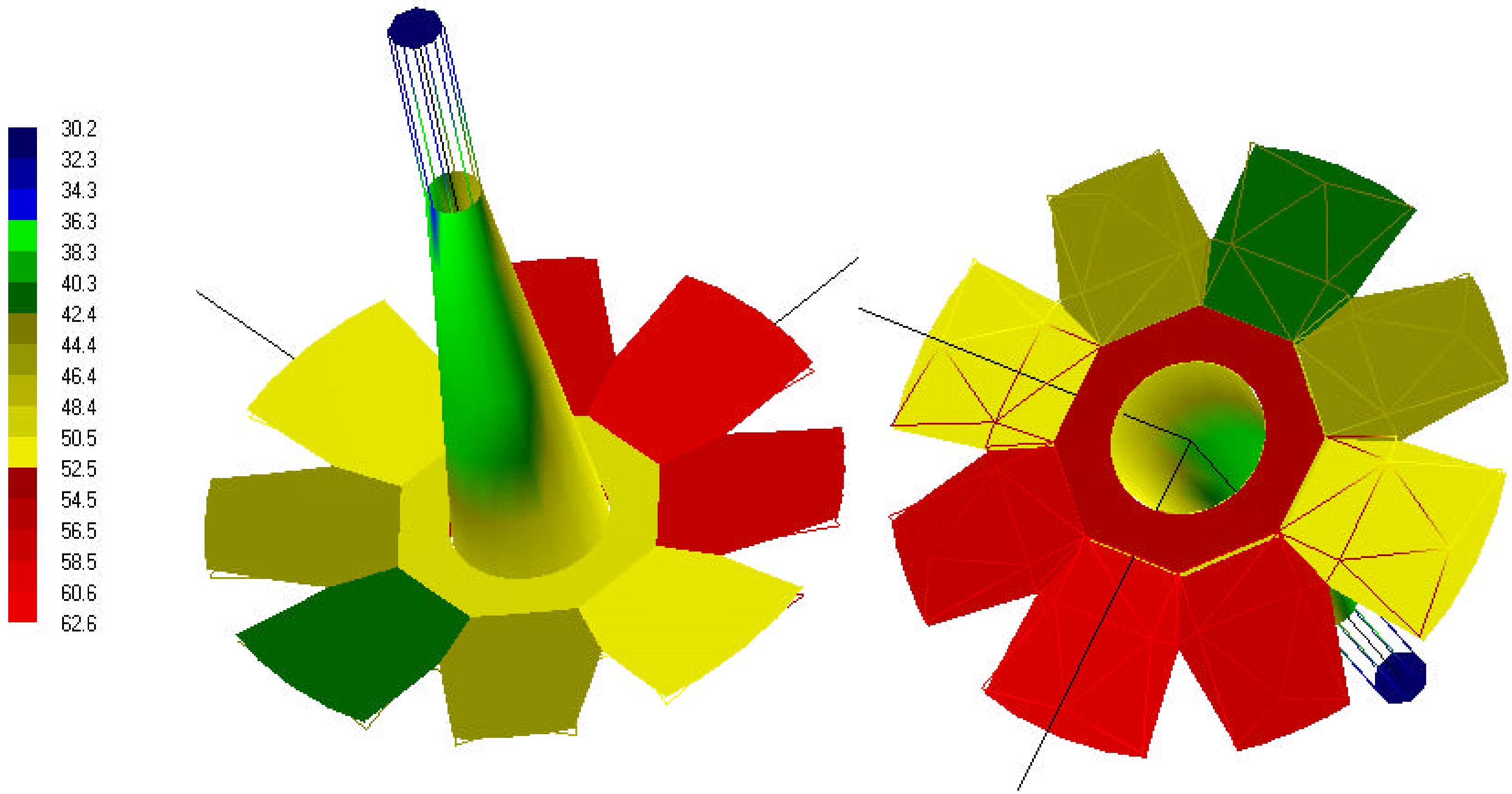
7-Hex



36-Hex



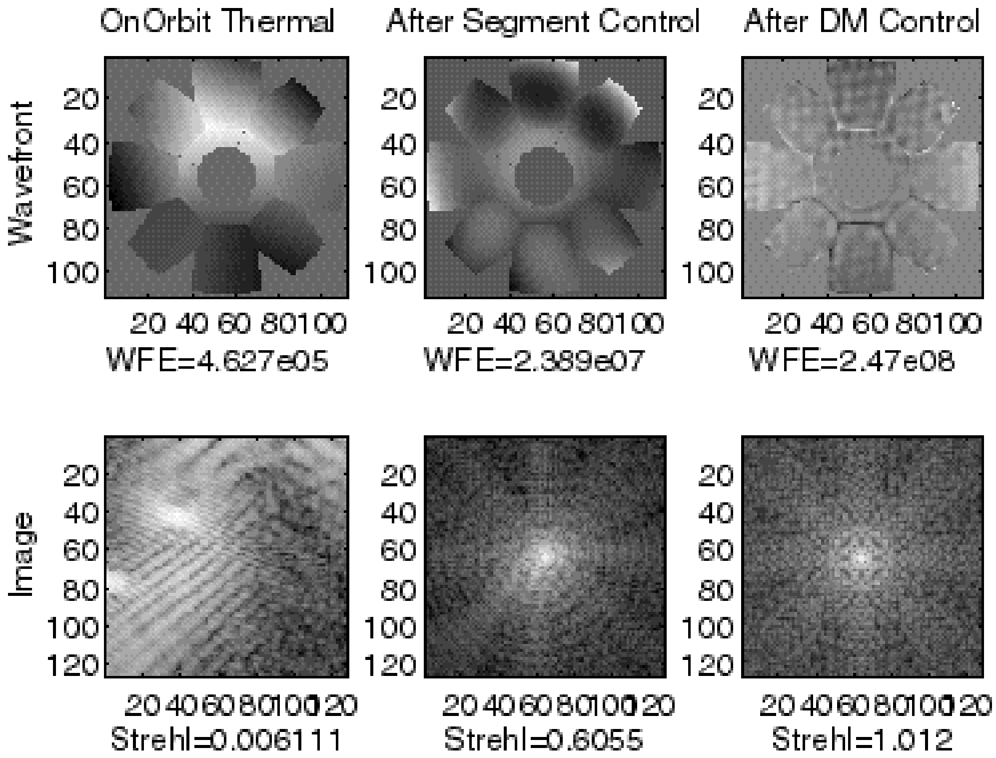
Thermal Performance



- On-Orbit Temperatures for All-Be OTA
- Beryllium facesheet and open-backed support structure

Thermal model by Greg Schunk, MSFC

Ground-to-Orbit Thermal Response



Beryllium OTA
Beryllium facesheet
Beryllium SM tower
FEM version 12/97

"Cold-figured" telescope
Telescope perfect at T = 100°K

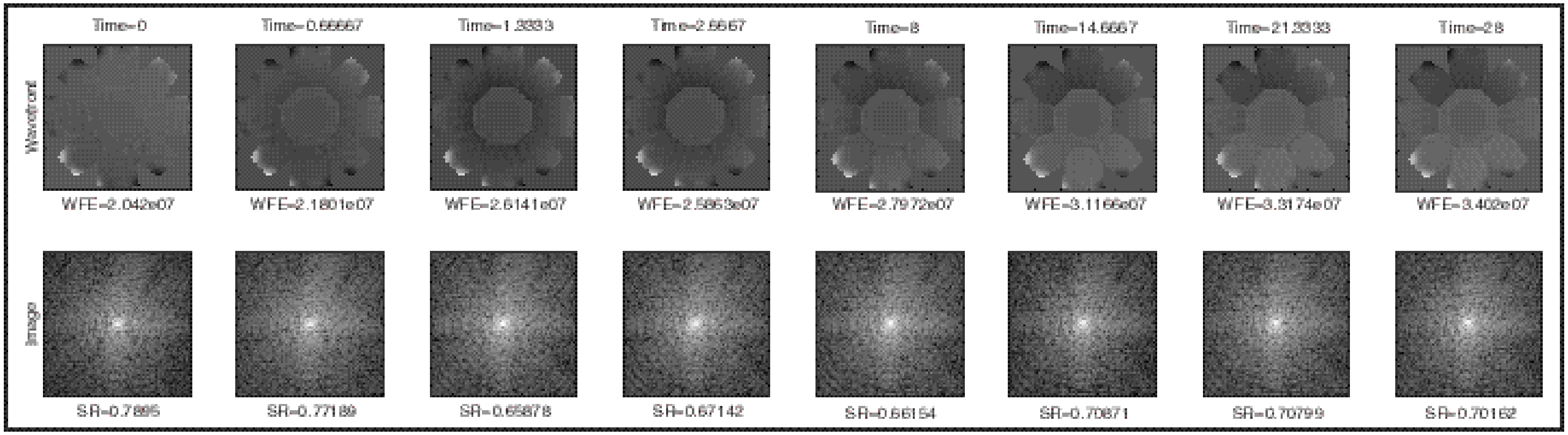
On-orbit T = 30 - 63 °K

Be CTE = 0.5 ppm
(integrated 100°K to 30°K)
Ti segment actuator CTE = 6 ppm

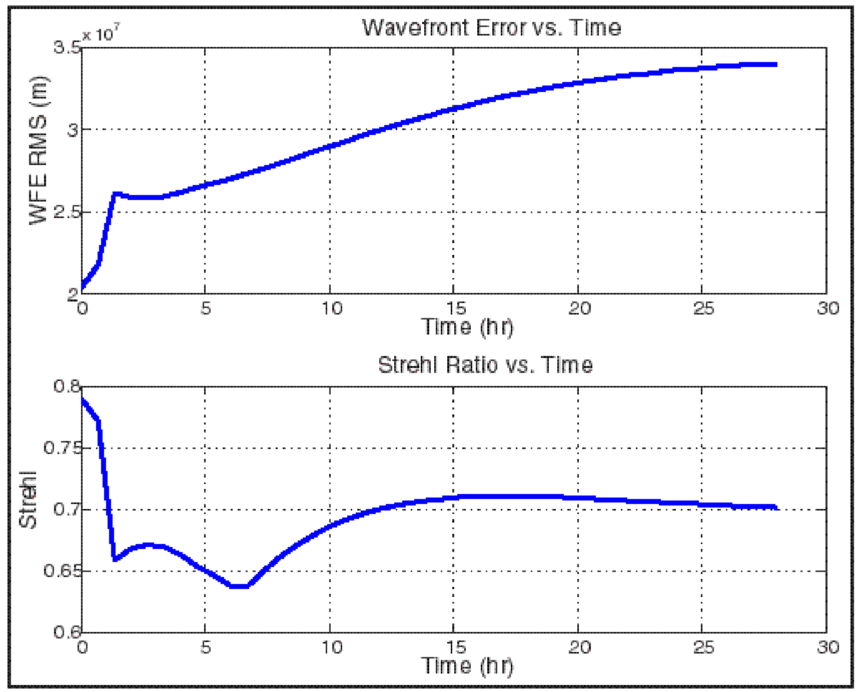
Wavelength = 2 um
Segment control in tip/tilt/piston DOFs only

- **"Cold figured" OTA: perfect at 100°K, deforms when cooled to operational temperature**
  - **Isotropic materials**
- **Compensated with 3DOF segment control, 349 DM actuator control**
- **Improvements can be made to meet goal of 100 nm WFE post-segment control**
  - **6 DOF segment control**
  - **Improved cryo figuring**

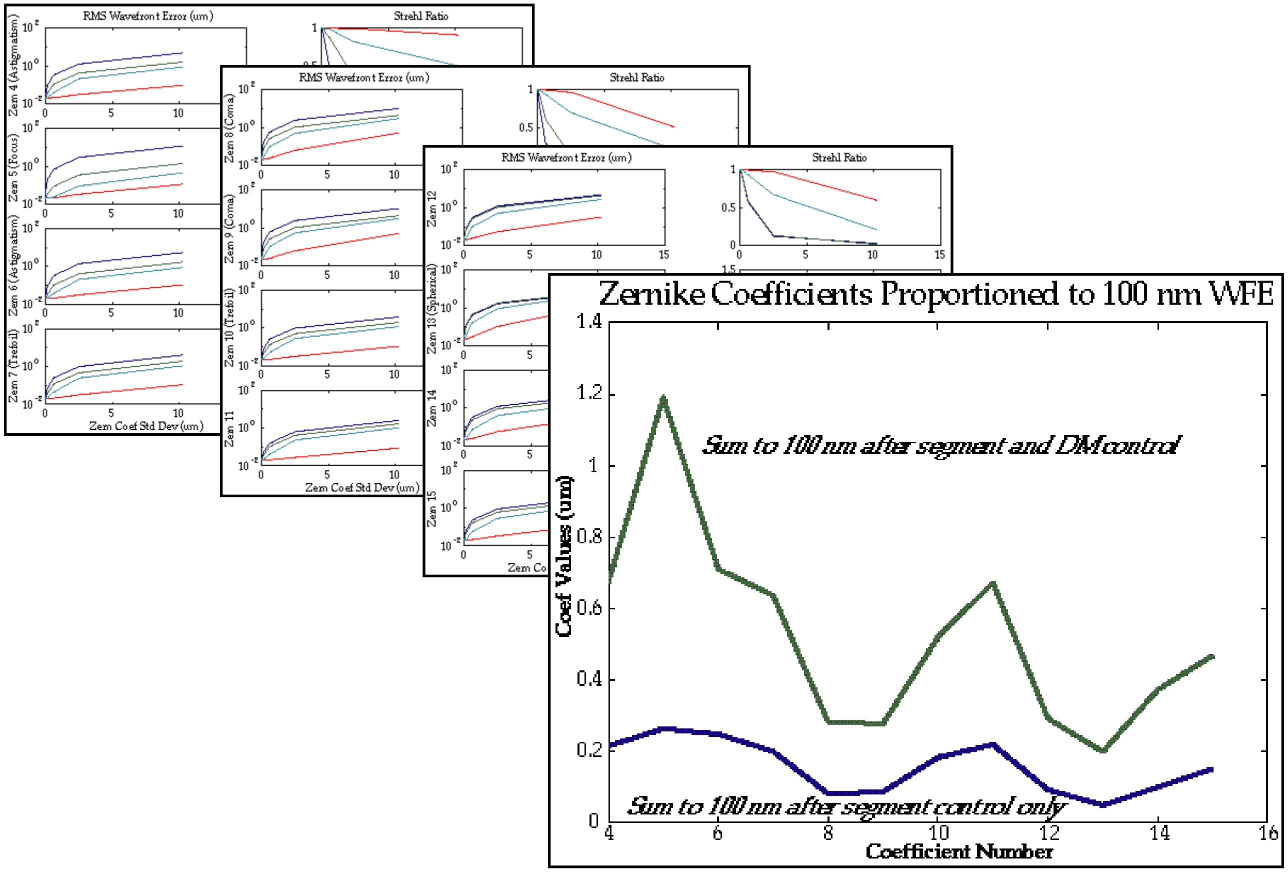
WF Stability During Observations



- WF control performed at hottest attitude
  - SR = 79%
- 1 hr slew to coldest attitude
- Steady state reached 28 hours later
  - SR = 70%



Post-WFC Figure Error Tolerances



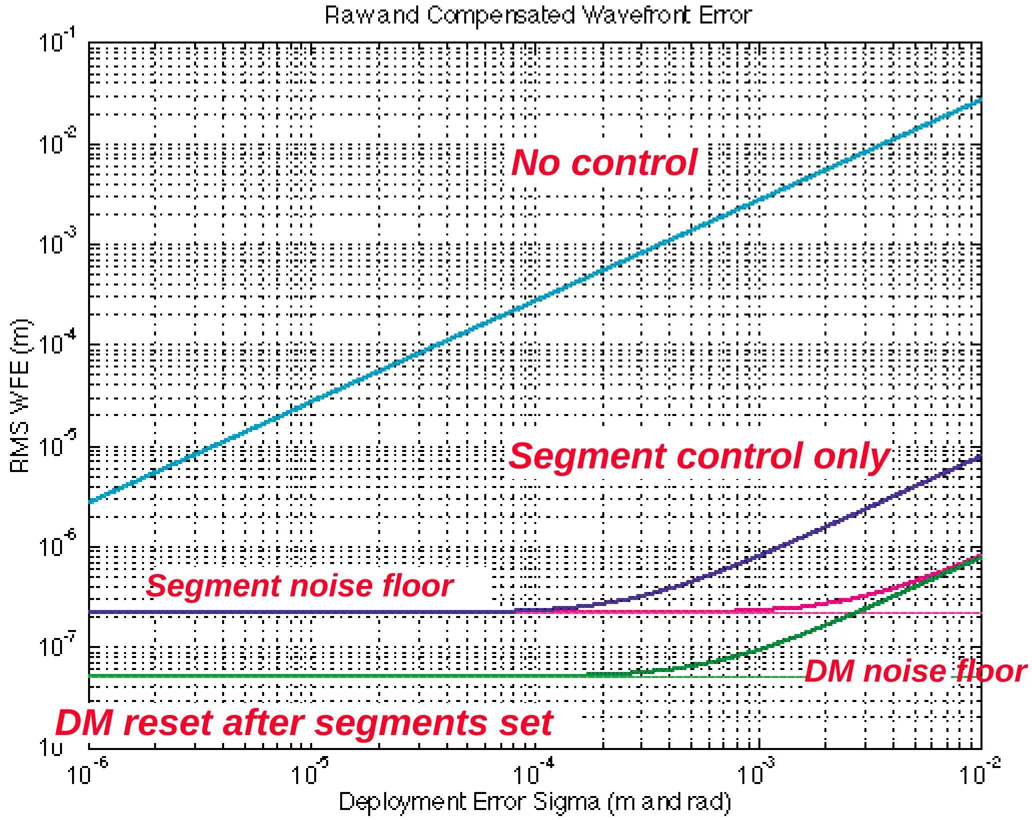
Low-Order Figure Error Budget

Total post-control WFE
100 nm

Term	Pre-control	Post-control
Z4	673 nm	43 nm
Z5	1191 nm	43 nm
Z6	711 nm	43 nm
Z7	637 nm	43 nm
Z8	283 nm	43 nm
Z9	278 nm	43 nm
Z10	520 nm	43 nm
Z11	673 nm	43 nm
Z12	292 nm	43 nm
Z13	199 nm	43 nm
Z14	373 nm	43 nm
Z15	469 nm	43 nm

- **WFC greatly reduces sensitivity to low- and mid-spatial-frequency figure errors from all sources**
  - **Thermal deformations**
  - **PM segment fabrication and polishing errors**

Post-WFC Deployment Error Tolerances

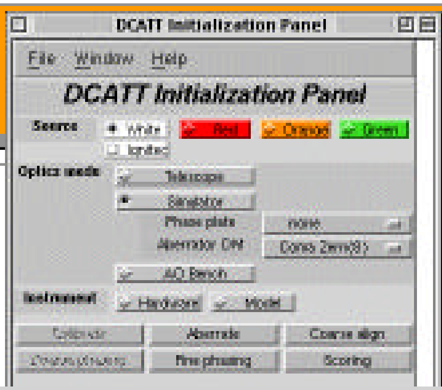


NGST 8-Petal configuration
8 meter aperture
F/1.25 primary
F/24 system
λ = 1.0 μm (0% bandpass)
Random initial segment state errors
Optimal WF controller
Set DM and segments together
Follow up with DM only
Phase sensing
Results via covariance analysis

Deployment error in 6DOF
Uniform variance
Segment actuation in 3DOF
Segment actuation error 8e-8 rad & m
DM actuation error 1e-9 m
Sensing error 1e-12 m

- **Segment control reduces WFE by 3e3, minimizes edge discontinuities**
- **DM control reduces WFE by an additional factor of 10**
- **DM control after segment actuation provides lower noise floor**

DCATT Testbed



- Performance verification
- Control software prototyping
- Model validation